Paper A 6

VEGETATION DENSITY AS DEDUCED FROM ERTS-1 MSS RESPONSE

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ABSTRACT

Reflectance from vegetation increases with increasing vegetation density in the 0.75- to 1.35-μm wavelength interval. Therefore, ERTS-1 bands 6 (0.7 to 0.8 μm) and 7 (0.8 to 1.1 μm) contain information that should relate to the probable yield of crops and the animal carrying capacity of rangeland. On the other hand, reflectance from vegetation is typically less from vegetation than from bare soil and is essentially constant in the visible wavelengths as vegetation density increases; consequently, the decreased response observed in ERTS bands 4 (0.5 to 0.6 μm) and 5 (0.6 to 0.7 μm) as vegetation increases is mainly caused by vegetation obscuring soil reflectance. The ratio of band 5 to band 7 (5/7) or band 7 minus band 5 (7-5) are, in addition to bands 6 and 7, practical indicators of vegetative cover and density for users of ERTS-1 data.

The results of an experiment designed specifically to test the relations among leaf area index (LAI), plant population, plant cover and plant height, and the ERTS-1 MSS responses for 3 corn, 10 sorghum, and 10 cotton fields are also given. Because of clouds, only one ERTS-1 pass (May 27, scene 1308-16323) yielded MSS data and that for only bands 4, 5, and 6. The coefficient for the linear correlation between LAI and band 6 digital counts was 0.823** for the 10 cotton fields and 0.841** for the combined sorghum and corn fields. The correlation coefficient between LAI and band 6 minus band 5 digital counts was 0.888** for cotton fields and 0.768** for the corn and sorghum fields. The four plant parameters explained 87 to 93% of the variability in the band 6 digital counts and from 59 to 90% of the variation in bands 4 and 5. Plant population was as useful as LAI for characterizing the sorghum and corn fields, and plant height was as good as LAI for characterizing cotton fields. These findings generally support the utility of ERTS-1 data for explaining variability in green biomass, harvestable forage and other indicators of productivity.

INTRODUCTION

The earth's vegetation is one of its most valuable resources. Plants are the traceable source of most of the food and fiber needed by humans and other animals, and past generations of plants provide the energy reserves of coal and petroleum that concern us today. Plants are also intimately involved in the hydrologic and energy balances of the earth.

Net assimilation, or dry matter production, by vegetation is related to the number and photosynthetic area of leaves. Fortunately, the spectral response observed when viewing vegetation from space is dominated by the leaves. Thus the spectral response of vegetation in the ERTS-1 data is worth examining in terms of vegetation cover, vegetation density, and other productivity indicators of range, forest, and crop land.

Agriculturalists, foresters, and range scientists use various parameters to indicate the vegetation density or potential productivity of vegetation. Foresters use tree girth, crown diameter, tree height, leaf area index, and timber volume. Range scientists use harvestable forage and animal carrying capacity (acres or hectares required to maintain an animal year round). Ecologists use estimates of biomass. Agriculturalists use leaf area index (LAI), percent ground cover, plant height, plant population per unit ground area, and other measures of vegetation conditions.

The purposes of this paper are (a) to point out the information available to ERTS users about vegetative cover and density in the ERTS-1 multispectral scanner (MSS) data and (b) to report data relating the MSS response to leaf area index (LAI), plant population, ground cover, and plant height.

LITERATURE REVIEW

ERTS-1 bands 4, 5, and 7 color composites yield images with color tones similar to those of color infrared photographic film. Thomas et al. (1966, 1967) and Stanhill et al. (1973), respectively, have shown that light reflectance from cotton and wheat fields is strongly affected by the amount of plant material or percent ground covered by the vegetation. In their studies, light transmission of color infrared film accounted for 75 and 49% of the variation in cotton lint and wheat grain yields, respectively.

Von Steen, Leamer, and Gerbermann (1969) found statistically significant correlations among preharvest yield indicators (open bolls, number of plants, percent ground cover, plant height, weight plant material per plot) and optical density of aerial infrared film for cotton, grain sorghum, carrots, cabbage, and onions.

Stoner, Baumgardner, and Cipra (1972) related the LAI of corn to the ratio of visible and reflective infrared channels of aircraft optical mechanical scanner data on two flight dates in July. The combined MSS data for the two flight dates yielded a coefficient of determination, R^2, of 0.968 between LAI, that ranged from 0 to 4, and the ratio of two MSS channels (1.0 - 1.4 μm/0.61 - 0.70 μm).

Pearson and Miller (1972) developed and tested both a two-channel ratioing technique and a multispectral pattern recognition technique to compare spectral biomass estimates of grassland with biomass values taken from clipped plots. Biomass estimates were made with an accuracy greater than 95% with a two-channel spectral ratio method using a small hand-held radiometer. Eighty to 90% of the variation in biomass values taken from clipped plots along a flight line could be explained by the airborne MSS data over the same area. Kanemasu (In Press) found that the ratio of reflectances at 0.545 and 0.655 closely followed crop growth and development and concluded that it was a good indicator of soil exposure and crop maturity.

A number of practical applications of the ERTS-1 data to determining vegetation types and amounts, or seasonal effects were previously reported (Freden, Mercanti, and Becker, 1973). For example, Carneggie and DeGloria (1973) obtained information from the ERTS-1 scenes of California on the distribution, yield, condition and availability of forage. Seevers and Drew (1973) identified gross differences in forage density and range condition within given range sites in the sand hills of Nebraska. Heath and Parker (1973) used computer-aided interpretations to classify timber stands and range plants in the Houston area. Dethier (1973) reported that the brown wave (fall vegetation senescence) could be readily detected in the Appalachian and Mississippi Valley corridors and suggested that specific phenological events such as crop maturity and leaf fall could be mapped for specific sites and possibly entire regions from the ERTS-1 data.

PRINCIPLES

The wavelengths of light that are effective for photosynthesis cover the interval from 0.4 to 0.7 μm. Bands 4, 5, 6 and 7 of the ERTS-1 MSS correspond to the spectral intervals 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, and 0.8 to 1.1 μm, respectively. Laboratory data on the spectral reflectance of leaves in terms of the number of leaf layers is given in Fig. 1, taken from Allen and Richardson (1968), except that the ERTS-1 MSS bands have been superimposed. Notice that in the 0.75- to 1.35-μm interval, the reflectance of vegetation is very high and that the signal strength increases as the number of leaf layers, or the vegetation density, increases. This finding indicates that ERTS-1 band 7 responses, and to a lesser extent band 6 responses, should clearly indicate differences in vegetation density.

There is a one-to-one correspondence between yield and vegetation density of crops grown for hay or forage. For plants grown for their seed, fruit, roots, or fiber, there is usually a close correlation between potential production and plant vigor. Axiomatically, healthy non-stressed plants develop larger and more dense canopies and yield better than those growing under suboptimal conditions.

The ERTS-1 responses can be related to the stage of crop development. Spectral crop calendars useful in temporal analyses are possible (Steiner, 1970; Lauer, 1971). The ERTS-1 responses can also be directly related to percent ground cover, plant height or other crop parameters that are correlated with reflectance.

Figure 1 also shows that in the interval 0.5 to 0.75 μm, the reflectance from vegetation is virtually the same regardless of the number of layers of leaves in the plant canopy. The implication here is that the photosynthetic potential of green plants can not be deduced directly from the photosynthetically active wavelengths. Physiological disturbances in plants that decrease chlorophyll content may be detectable, compared with healthy plants, because chlorophyll is a strong absorber of visible light. Thus, the ERTS-1 bands 4, 5, and 6 are valuable to help identify deviations from healthy plants. Plants with physiological disturbances are less vigorous than healthy plants as manifested by fewer leaves or foliar discoloration (Wiegand, Gausman, and Allen, 1972). The information about plant density inferred from the reflective infrared bands 6 and 7 and the information about plant pigmentation obtained from bands 4 and 5 complement each other.

In ERTS-1 bands 6 and 7, the observed reflectance of the soil background is usually less than that of vegetation whereas in bands 4 and 5 it is typically greater than that of vegetation. Therefore, in ERTS-1 band 4 and 5 wavelengths, the soil background dominates the signal up to a fairly high vegetative cover.

Because the ERTS-1 MSS signals recorded for variable ground cover conditions (vegetation density conditions) are a mixed signal for soil and vegetation, the ratio of band 5 to band 7 (5/7) or band 7 minus band 5 (7-5) are practical indicators of vegetative cover and density for users of ERTS-1 data. The decreased radiance observed in ERTS-1 bands 4 (0.5 to 0.6 μm) and 5 (0.6 to 0.7 μm) as vegetation density increases is mainly caused by the increasing amount of soil obscured by the vegetation.

Vegetation density is also dependent on stage of the growing season, or time of the year. Deciduous trees shed their leaves in fall but conifers retain theirs. Thus the two are best contrasted when the deciduous trees are dormant. The progress of the vernal advance (green wave) and fall senescence (brown wave) can be assessed for natural stands of plants and cultivated perennials. Development of annual crops can also be monitored and be interpreted in relation to major weather events such as freezes, drought, and rainfall distribution.

Figure 2 presents the observed radiometric response of the MSS bands 4, 5, and 6 for one corn and two sorghum fields in ERTS-1 scene 1308-16323 that had ground cover of 55, 90, and 90% and LAI of 2.46, 4.08, and 6.92. Also shown is the spectrum for bare soil (Mercedes clay). The radiances (Potter, 1972; conversion factors from digital counts to radiances are .19528, .15748, .13858, and .24286 for bands 4, 5, 6, and 7, respectively) decrease in bands 4 and 5 with increasing vegetation density, expressed as LAI, or with the increasing amount of soil obscured by the plants. The radiances in band 6 are in the order of LAI. The missing band 7 radiances should be about the same or slightly higher than those for band 6, but unlike band 6 they should be pure reflective infrared responses and not a mixture of visible and reflective infrared signals. The band 6 radiances do yield spectra similar in shape to the data for stacked leaves measured with a laboratory spectrophotometer given in Fig. 1. The radiance values for bare soil were obtained from a bare field close to the grain sorghum fields in the ERTS-1 scene. Compared with other ERTS-1 scenes, the radiance in band 6 is high for the particular bare field represented in Fig. 2.

THEORY

Allen and Richardson (1968) applied the Kubelka-Munk theory to reflectance of light by plant canopies and produced the equation

$$LAI = \frac{1}{2 \ln b} \ln \frac{(a-R)(1-aRg)}{(a-Rg)(1-aR)} \qquad [1]$$

for predicting leaf area index (LAI) of plant canopies from their reflectance measured remotely. The equation applies over the reflective infrared plateau wavelength interval, 0.75 to 1.35 μm. In eq. [1], R is the canopy reflectance, Rg is the reflectance of the soil background, and a and b are optical constants that have been determined for many plants (Gausman and Allen, 1973; Allen, Gausman, Richardson, and Wiegand, 1970; Gausman et al., 1973).

A completely different total reflectance model in terms of fractional plant cover can be expressed by

$$R_T = f\,Rc + (1-f)\,Rg \qquad [2]$$

wherein R_T is total reflectance, Rc is vegetation canopy reflectance, Rg is soil background reflectance, and f is an indicator of plant density, such as, percent ground cover, LAI, or plant height.

Upon rearranging eq [2],

$$R_T = Rg + (Rc-Rg)f. \qquad [3]$$

Comparing eq. [3] with the standard linear regression model

$$R_T = a_o + a_1 f \qquad [4]$$

it is seen that

$Rg = a_o$, the reflectance intercept when f = o, and

$(Rc-Rg) = a_1$ so that $Rc = a_o + a_1$.

Rc is the reflectance characteristic of the crop or plant community the data are from. If f is expressed in LAI, then it is the reflectance of the canopy with a leaf area index of unity. If in percent ground cover, it is the reflectance of the canopy when ground cover is 1%. In the ERTS-1 MSS signals, R_T is a mixed signal for the vegetation and soil background. The simplified model presented enables one to estimate Rg, and the regression coefficient (Rc-Rg) identifies the rate of change of reflectance per unit change in f.

As shown in Fig. 1 and discussed by Wiegand et al. (1971), the reflectance of vegetation in the visible region (ERTS-1 bands 4 and 5) is virtually the same for leaves one layer deep or stacked in enough layers to insure infinite reflectance, R_∞ (Allen and Richardson, 1968), and usually lower than that of soil. Thus R_T should be virtually constant for vegetation once the soil is obscured, and (Rc-Rg) in eq. [3] should be small and negative. In the reflective infrared, however, R_T should increase as the vegetation density increases up to a LAI corresponding to R_∞, requiring that (Rc-Rg) be positive.

R_T and Rc are expressed in the ERTS-1 MSS signal by the digital counts of the system-corrected digital tapes, by the data expressed as radiance (Potter, 1972), or as a normalized response relative to the digital count maximum (127 for bands 4, 5, and 6 and 63 for band 7) for each band. Calibration of the MSS data directly in terms of reflectance needed for eq. [1] is not available to the authors.

In practice ERTS-1 data users will want to express the MSS responses in terms of quantities that are highly correlated with reflectance--dry matter production, biomass, LAI, percent ground cover, e.g. Once the relation is calibrated for a particular crop, plant community, or ecosystem of interest, the ERTS-1 data should be expressible directly in the productivity estimator of interest to the user. Atmospheric conditions that vary from one ERTS-1 pass to another should shift the data along the axes for any one band, but should not greatly affect the relative position of the data points to each other. If differences between two bands

are used, such as band 7 minus band 5, atmospheric interference effects are reduced possibly permitting pooling of data from multiple ERTS-1 passes for analysis. A ratio of responses in bands both in the visible, as 4/5, or both mainly in the infrared, as 6/7, should minimize atmospheric interference effects in the absence of random noise since both numerator and denominator would be similarly affected by atmospheric attenuation.

METHODS

Data being presented in this paper arise from two different sources. One source is the ground truth that has been taken to support the ERTS-1 analysis effort for one whole county. It was taken to (a) have well-documented fields to judge the accuracy of ERTS-1 classification results against, (b) provide statistical estimates of the acreages devoted to various crops to compare with ERTS-1 estimates, and (c) help establish what ground truths are meaningful in terms of the ERTS-1 spectral data. The data consist of observations of the soil surface condition, species, plant height, percent ground cover by the crop and by weeds, stage of plant maturity, and observations on the general condition of the crop, and stresses in four interpenetrating samples located throughout the county. Almost 1500 fields are involved.

The other source of data is an experiment conducted in the spring of 1973 specifically to determine the leaf area index (LAI) of 3 corn, 10 grain sorghum, and 10 cotton fields selected from the 1500 fields to have a range in planting dates, hence crop maturity, over several ERTS passes. The overall purpose was to test eq. [1] using the ERTS-1 data. Ten average-sized plants were cut off at ground level at each of eight sites in each field, the leaves were removed, and the area of each leaf was determined using a photoelectric planimeter. The area of the leaves was cumulated for each plant and sampling site and expressed as the ratio of area of the leaves to the ground area occupied by the plants. This ratio is by definition, LAI.

The number of plants per 10 m segments of row was determined on four adjacent rows at each of eight locations in each field to establish the plant population and hence the LAI characteristic of each field. The LAI determination was to be repeated each 2 weeks in each field between April and June to insure data near ERTS-1 overpasses. However, the large manpower requirement for LAI determinations and heavy rainfall prevented maintenance of the schedule.

The procedure used to determine the percent of ground covered by the plant canopies differed depending upon whether the crop plants produced a solid canopy (bare soil exposed only in the inter-row area) or an open canopy (bare soil visible through the canopy as well as in the inter-row area). For the solid canopy crops, such as cotton and thick stands of corn and sorghum, the bare soil width (BW) and row spacing (RS) were measured. By definition, BW is the width of the bare soil showing between the leaf canopies of adjacent crop rows, and RS is the average spacing between crop rows. For the solid canopy the percent crop cover is calculated from these measurements using

$$\left(\frac{RS - BW}{RS}\right) 100 = \text{percent cover}$$

where RS and BW are measured in cm.

For the open canopy crops--such as onions, immature cantaloupe, and corn and sorghum planted to low plant populations--the "open" canopies were considered solid, and the above formula was used to determine the percent cover. Then a subjective estimate was made of the percent open spaces in the leaf canopy by looking downward on them and this percentage was subtracted from the estimate calculated by the formula to obtain an estimate of actual cover

The computer compatible digital tapes (CCT) from the National Data Products Facility (NDPF) were displayed on a cathode ray tube (CRT), and a coordinate system was overlain to aid in locating the fields of interest in the CCT. The digital data corresponding to the approximate coordinates of the fields and sample segments of interest were transferred to a secondary tape. These data were displayed as gray maps using a line printer and were intensively studied to establish field locations and field boundaries. The digital counts for the pixels, or instantaneous ground resolution elements, within the test fields were averaged for each MSS band.

The space data were used as (a) digital counts, (b) radiance (mw/cm^2-sr-µm) using the conversion factors provided by Potter (1972), or (c) pseudo-reflectance by ratioing the CCT digital counts by the maximum possible count (127 for bands 4, 5, and 6 and 63 for band 7).

RESULTS

Due to excessive clouds, data are available for only three ERTS-1 passes, Dec. 16, 1972, Jan. 21, 1973, and May 27, 1973, corresponding to scene I.D. 1146-16323, 1182-16322, and 1308-16323, respectively. The May 27 scene is the only one for which LAI data are available; ERTS band 7 data for this scene delivered to date have a "venetian blind" effect in them and are not useable. The NDPF is redigitizing this scene.

Figures 3a and 3b present the relation between LAI and band 6 digital counts, the band 6 minus band 5 digital count difference, and the ratio of digital counts in bands 5 and 6 (5/6) separately for the combined grain sorghum and corn fields and for the cotton fields. LAI of sorghum and corn account for 67.7% of the variation in band 6 digital count, 59% of the variation in the 6-5 difference, and 45.2% of the variation in the band 5/6 ratio. Thus band 6 alone is superior to the difference, and to the ratio of visible-to-infrared response.

For the cotton fields, a quadratic equation was used to fit the band 6, and the band 6 minus band 5 optical count difference but a linear equation was fitted to the 5/6 ratio data. LAI explains 83%, 90%, and 78% of the variation in digital counts using band 6, 6-5, and 5/6, respectively. For cotton, then, the band 6 minus band 5 digital counts were the best indicator of vegetation density.

The sorghum and corn plants averaged 94 cm high and were approaching full canopy development, whereas the cotton plants averaged only 37 cm in height and were at or very near first bloom stage of development. The plants also differ considerably in growth habit or architecture. Corn and grain sorghum display their long curved leaves in umbrella fashion, whereas cotton plants are conical and their leaves are heliotropic. Such characteristic differences help to discriminate among crops and plant communities spectrally and must contribute useful information for texture analyses. They also suggest that crops or plant communities typical of a given locale or region might be spectrally "calibrated" against the ERTS-1 data one or more times during the year; identifications in subsequent years would be based on the calibration so that extensive ground truth would be unnecessary.

Most investigators use the ERTS-1 MSS digital counts as provided by the NDPF system-corrected CCT. Table 1 presents the linear and quadratic equations for the regression of CCT digital counts (DC) on LAI. For cotton, the quadratic equation explained a statistically significant amount of variance over the linear equation, but it did not for sorghum. The equations for band 6 are repeated from Figs. 3a and 3b but the equations for bands 4 and 5 are presented anew.

The sorghum and corn plants obscured the soil so the correlation in the visible, where responses are due mainly to soil, are poor. For the cotton, both the exposed soil and the vegetation yielded an appreciable signal so that correlation coefficients in both the visible and infrared are significant at 0.01 probability level. The improvement in fit for cotton using a quadratic expression is appreciable, and suggests that a more complicated physical model is required when plant cover is incomplete. Three considerations are sun angle as it affects the length of shadows cast by the plants, row direction, and row spacing.

LAI is only one measure that agriculturalists use to indicate vegetation density. The simple correlations between LAI and plant population (POP; plants per 40 meters of row), percent ground cover (PC), and plant height (PH) are given in table 2 as well as the multiple regression equations expressing LAI as a function of the other plant parameters. LAI of cotton is most highly correlated with PH (0.783) and least correlated with plant population (0.382), whereas LAI of sorghum and corn is most highly correlated with plant population (0.829) and least correlated with PH (0.165). These data seem to indicate that different plant parameters are needed to characterize different crops.

Any useful plant and soil parameters for characterizing crop, range, and forest scenes must necessarily account for most of the variation in the MSS data. Table 3 summarizes regression equations produced relating the CCT digital counts to the vegetation ground truths: LAI, plant population (POP), plant cover (PC), and plant height (PH).

As expected, the plant parameters explain more of the variation in digital counts in the reflective infrared than in the visible. The regression coefficient for the population term was zero for sorghum and corn in bands 4 and 5, causing this variable to be dropped from the estimating equation. Evidently the high correlation ($r = 0.829$) between LAI and POP shown in table 2 caused plant population to contribute nothing to the estimation of the digital counts that was not explained by LAI. This finding has practical consequences. Plant population is easy to determine by counting stalks at a number of locations in fields, or it can be estimated from the amount of seed planted per hectare. Determination of LAI, on the other hand, is laborious and the plants are destroyed in the process. Thus if plant population suffices to characterize corn and sorghum fields in terms of LAI and ERTS-1 radiances, verifying ground truth is easy to obtain. Of course, the plant population remains constant once a crop stand is established. The plants would grow and the radiances measured by satellite would change from one satellite pass to another as the plants develop. However, the radiances for a given set of fields would remain in the same relative position to each other as the plant populations do. Thus one population count should be good for a whole growing season (several ERTS passes).

If there is a good relation between plant population or ERTS radiances and yields, a procedure is suggested for determining the optimum population on a regional basis. Then one can work to get the optimum population widely adopted by growers.

As shown in table 2, PH for cotton was highly correlated with LAI. Coefficients for the linear correlation of LAI and PH with DC calculated in arriving at the equations of table 3 were:

			Band 4	Band 5	Band 6
				r	
DC	vs	LAI	-.726**	-.855**	+.823**
DC	vs	PH	-.769**	-.825**	+.925**

The similarity among correlation coefficients for the correlation of LAI and PH with DC in all bands and the very high coefficient for the correlation of DC with PH in band 6, suggest the possibility that PH can substitute for LAI at least during the prebloom and early fruit set periods of development of this crop.

The 93.4% and 87.3% (R^2 x 100) of the variation in digital counts explained in band 6 for cotton and the combined sorghum and corn, respectively, by the plant parameters used to characterize the crops indicate that (a) characteristics of the vegetation are mainly responsible for the recorded ERTS-1 signals, and (b) useful plant parameters are available for the crops studied.

As stated earlier, one objective of this study was to test eq. [1] for predicting LAI from the ERTS MSS data. Table 4 gives the optical constants a and b, defined by Gausman and Allen (1973), needed to solve eq. [1]. They are calculated from absolute reflectance and transmittance spectra obtained spectrophotometrically on leaves typical of the crops. The values given for "sorghum and corn" are an average of values for each of the two crops.

Inspection of eq. [1] shows that it is limited to conditions when the canopy reflectance R is larger than the soil background reflectance. Additionally, the last term becomes negative if 'a' gets very large.

LAI was calculated for band 6, using the digital count observed in the MSS data divided by 127 to obtain a pseudo-reflectance of the crop, R, and the intercept of the pseudo-reflectance at LAI = 0 was used as the reflectance of the soil background.

The coefficients for the linear correlation of calculated LAI with manually measured LAI were high at 0.815** for cotton and 0.872** for sorghum and corn, respectively. However, the calculated LAI never exceeded 2.0. Thus the predictions of LAI from eq [1] are not satisfactory.

The possible reasons for poor results include (a) the constants 'a' and 'b' are in inappropriate units for this application, (b) the pseudo-reflectance used is inappropriately normalized, (c) band 7 MSS data should be used, (d) the reflectance for soil estimated from the intercept at f = o is too high, (e) the theoretical requirements of the equation (diffuse isotropic incident radiation) are not met, and (f) the row pattern of crops distributes the leaves nonuniformly against the background. Optical constants derived from laboratory data have been successfully applied to other field studies.

Efforts to use eq. [1] will continue because of the potential it has as a practical tool for deducing biomass or yield from ERTS-1 and other remotely measured near-infrared reflectance.

The second model proposed, typified by eq. [3], was also applied. It should describe the physical events better in the visible (bands 4 and 5) than in the infrared; in the infrared it is too simple to describe the multiply-reflected light from successive leaf layers. In applying eq. [3] the digital counts from the ERTS-1 data, R_T, are plotted against any plant parameter of interest such as fractional cover, LAI, or even plant height. Rg is the intercept on the R_T axis when fractional ground cover, LAI, or height of the plants of interest is zero, that is, the soil is bare.

Table 5 gives the values of Rg, (Rc-Rg) and R_T calculated from eq. [3] for each MSS band for the three ERTS-1 scenes we have data from. For the May 27 pass, the calculated R_T value is given as a function of LAI, but for the other two dates as a function of percent ground cover. The calculated R_T values increase from the Rc value in the infrared bands as vegetation density increases from LAI = 1, but decrease in the visible with increasing LAI above 1. Even though LAI for the cotton plots ranged up to 3.0, the ground cover was only 18 to 40%; consequently considerable soil reflectance should be recorded in the ERTS signals. The measured LAI ranged up to 8.5 in the sorghum and corn fields, but the ground cover recorded ranged from 35 to 90%. Consequently some soil (or shadow) signals were included even for fields with high LAI.

The January 21, 1973, data represent 28 vegetable fields as follows: broccoli, 2; carrot, 6; cabbage, 6; onion, 8; tomato, 3; lettuce, 1; beet, 1; and spinach, 1. Ground cover ranged from 2 to 90%. The December 16, 1972, data represent 106 vegetable fields consisting of crop and number of fields, respectively, as follows: lettuce, 14; pepper, 5; tomato, 11; onion, 26; cabbage, 19; carrot, 25; broccoli, 5; and beet, 1. Percent ground cover of these fields ranged from 1 to 100%. The regression coefficient (Rc-Rg) is negative on all dates for the visible bands and positive for the reflective infrared bands.

The digital count values for the May 27 ERTS-1 scene are higher than for the other two scenes. The predominant soil type for the December 16 and January 21 data is Harlingen clay and other heavy-textured alluvial flood plain soils. The May 27 data were obtained from upland soils further from the Rio Grande, which are as light-textured as fine sandy loam. Local soils are generally more reflective the coarser the texture. This, combined with the higher incident solar radiation in May than in December or January would account for the higher digital count values in the scene in May than in the winter months. The higher (Rc-Rg) values in May than the winter months for vegetation also agree with the larger digital counts being due to more incident solar radiation available for reflectance in May than in winter. For all scenes, the ERTS-1 MSS operated on low gain, hence MSS gain is not a factor.

In summary, we have shown that the ERTS-1 MSS data do relate to vegetation density and potential productivity and that vegetation parameters explain most of the variation in band 6 and 7 responses. We also presented and discussed two different equations for relating vegetation reflectance to the ERTS-1 MSS responses. We trust that operational methods for assessing the condition and animal carrying capacity of rangeland and the yield of crops using space data will incorporate procedures based on the principles presented.

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Table 1. Linear and quadratic equation regressions of ERTS-1 MSS digital counts (DC) on leaf area index (LAI) for bands 4, 5, and 6, scene ID 1308-16323.

Crop(s)	Band	Regression equation	Correlation coefficient
Cotton	4	$DC = 43.8-3.5(LAI)$	$r = -0.746$*
		$DC = 47.5-11.0(LAI)+2.5(LAI)^2$	$R = 0.867$**
	5	$DC = 40.0-5.0(LAI)$	$r = -0.856$**
		$DC = 42.6-10.3(LAI)+1.8(LAI)^2$	$R = 0.888$**
	6	$DC = 50.2+5.1(LAI)$	$r = 0.823$**
		$DC = 45.5+14.4(LAI)-3.1(LAI)^2$	$R = 0.911$**
Sorghum & Corn	4	$DC = 42.9-0.9(LAI)$	$r = -0.441$
	5	$DC = 38.8-1.5(LAI)$	$r = -0.464$
	6	$DC = 44.4+2.8(LAI)$	$r = 0.841$**

**Statistically significant at the 0.01 level.

*Statistically significant at the 0.05 level.

Table 2. Simple correlation coefficients among LAI and plant population (POP), percent cover (PC), and plant height (PH) for cotton and for grain sorghum and corn, and LAI expressed as a function of the other plant parameters.

CROP		POP (Plants/40m of row)	PC %	PH (cm)
		----------	r	----------
Cotton	LAI vs:	0.382	0.589	0.783**
	$LAI = -2.392-0.00003(POP)+0.0211(PC)+0.0829(PH)$			
	$R^2 = 0.628$			
Sorghum & corn	LAI vs:	0.829**	0.555**	0.165
	$LAI = 0.234+0.0023(POP)+0.038(PC)-0.0046(PH)$			
	$R^2 = 0.753$			

**Significant at the 0.01 level.

Table 3. Digital counts (DC) in ERTS-1 bands 4, 5, and 6 as estimated from four plant parameters, LAI, plant population (POP), percent ground cover (PC), and plant height (PH).

Crop	Band	Regression Equation	R^2
Cotton	4	DC = 47.51-2.215(LAI)-.006(POP)+.369(PC)-.367(PH)	.899**
	5	DC = 48.40-3.270(LAI)-.009(POP)+.006(PC)-.175(PH)	.853**
	6	DC = 31.09+1.243(LAI)+.005(POP)+.236(PC)+.391(PH)	.934**
Sorghum & corn	4	DC = 53.38-.600(LAI)-.034(PC)-.098(PH)	.590**
	5	DC = 56.11-1.049(LAI)-.023(PC)-.192(PH)	.653**
	6	DC = 45.93+3.09(LAI)-.00001(POP)-.111(PC)+.060(PH)	.873**

**Significant at the 0.01 level.

Table 4. Optical constants a and b for cotton, sorghum, and corn needed to solve eq. [1] over the ERTS-1 MSS wavelengths. Eq. [1] applies best to the reflective infrared wavelength interval 0.75 to 1.35 μm.

Wavelength	Cotton		Sorghum and Corn	
μm	a	b	a	b
.50	10.1149	12.4133	7.2990	28.2740
.55	8.3252	7.5888	5.9500	11.1809
.60	12.4855	14.4815	7.9804	34.5618
.65	13.0149	24.0333	9.8553	235.3162
.70	3.1282	2.9818	3.5587	3.9962
.75	1.4551	1.4357	1.4636	1.4417
.80	1.3295	1.3161	1.3193	1.2968
.85	1.3178	1.3024	1.2939	1.2706
.90	1.3446	1.3251	1.2914	1.2659
.95	1.4000	1.3736	1.3422	1.3082
1.00	1.3546	1.3318	1.3013	1.2704
1.05	1.3015	1.2825	1.2483	1.2224
1.10	1.3462	1.3226	1.2702	1.2408
1.15	1.5294	1.4858	1.4426	1.3885
1.20	1.5337	1.4875	1.4426	1.3862
1.25	1.5097	1.4640	1.4038	1.3504
1.30	1.6882	1.6114	1.5390	1.4596
1.35	2.0774	1.9230	1.8046	1.6679
1.40	4.2764	3.5637	3.3571	2.9117

Table 5. Digital count values of Rg, Rc, and R_T calculated using eq.[3] for ERTS-1 MSS bands 4, 5, 6 and 7 from three ERTS-1 scenes.

ERTS Scene and Date	Crop	Band	Rg	(Rc-Rg)	R_T LAI 1	2	4	6	8
			Digital Counts						
1308-16323 5/27/73	Cotton	4	43.8	-3.5	40.3	36.8	29.8	--	--
		5	40.0	-5.0	35.0	30.0	20.0	--	--
		6	50.2	+5.1	55.3	60.4	70.6	--	--
	Sorghum and Corn	4	42.9	-0.9	42.0	41.1	39.3	37.5	35.7
		5	38.8	-1.5	37.3	35.8	32.8	29.8	26.8
		6	44.4	+2.8	47.2	50.0	55.6	61.2	66.8
			DC	$\%^{-1}$	PC (%) 10	20	40	60	80
1182-16322 1/21/73	Vegetables (8 crops; 28 fields)	4	27.82	-.024	27.6	27.3	26.9	26.4	25.9
		5	25.63	-.058	25.0	24.5	23.3	22.2	21.0
		6	20.69	+.180	22.5	24.3	27.9	31.5	35.1
		7	26.59	+.187	28.5	30.3	34.1	37.8	41.5
1146-16323 12/16/72	Vegetables (8 crops; 106 fields)	4	31.35	-.037	31.0	30.6	29.9	29.1	28.4
		5	28.60	-.065	27.9	27.3	26.0	24.7	23.4
		6	29.91	+.063	30.5	31.2	32.4	33.7	35.0
		7	28.65	+.108	29.7	30.8	33.0	35.1	37.3

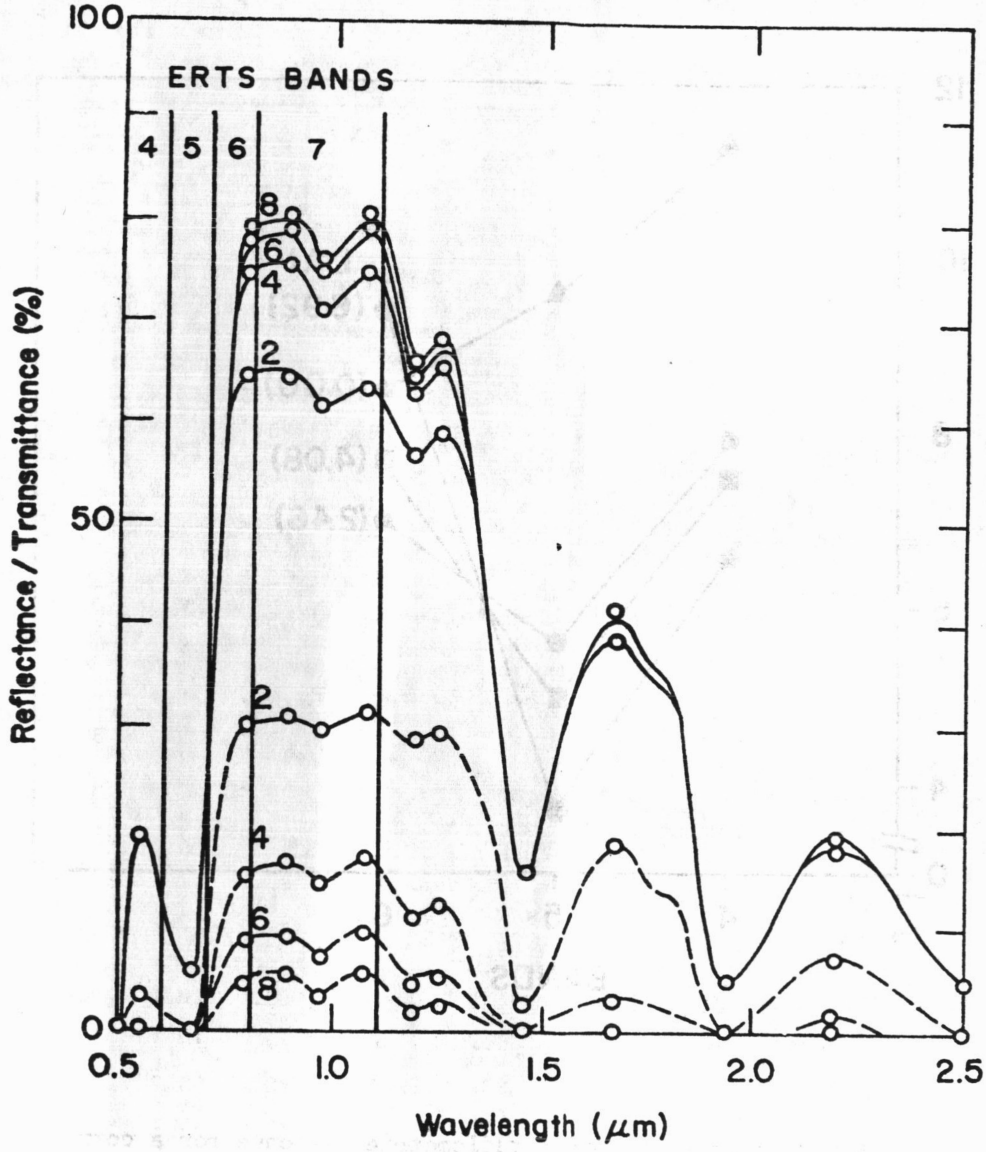

Fig. 1. Reflectance (solid lines) and transmittance (dashed lines) of 2, 4, 6, 8, stacked mature cotton leaves. The lines are theoretical; the circles are experimental. (Allen and Richardson, 1968.) Reflectance from vegetation is dependent on leaf area index in ERTS bands 6 and 7 but not in bands 4 and 5.

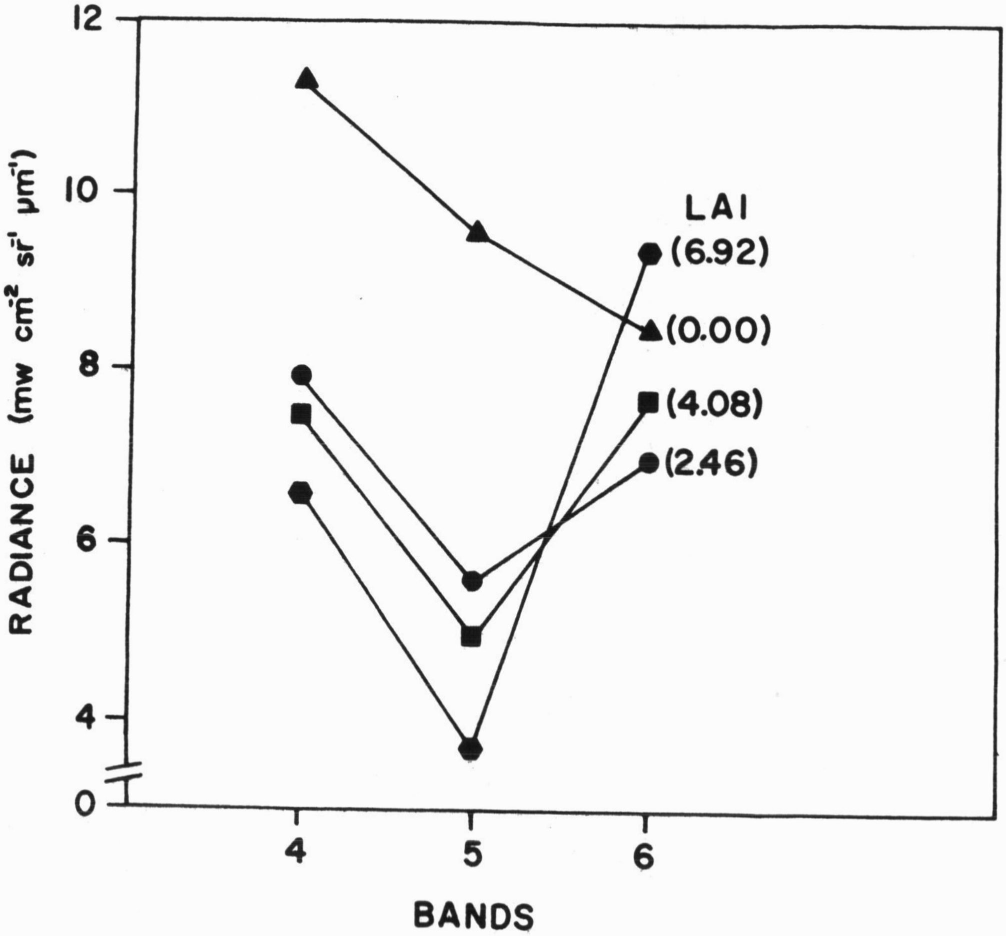

Fig. 2. ERTS MSS bands 4, 5, and 6 radiometric response for a corn, two sorghum, and a bare soil field with leaf area to ground area (leaf area index, LAI) of 2.46, 4.08, 6.92, and 0.0, respectively. ERTS response in bands 4 and 5 is mainly due to the soil obscured by vegetation, whereas in the reflective infrared vegetation dominates the ERTS signals. Note: Radiance of bare soil is that observed in ERTS data for lone bare field located near sorghum fields; its radiance is believed to be atypically high by approximately 2 mw cm^{-2}-sr^{-1}-µm^{-1}.

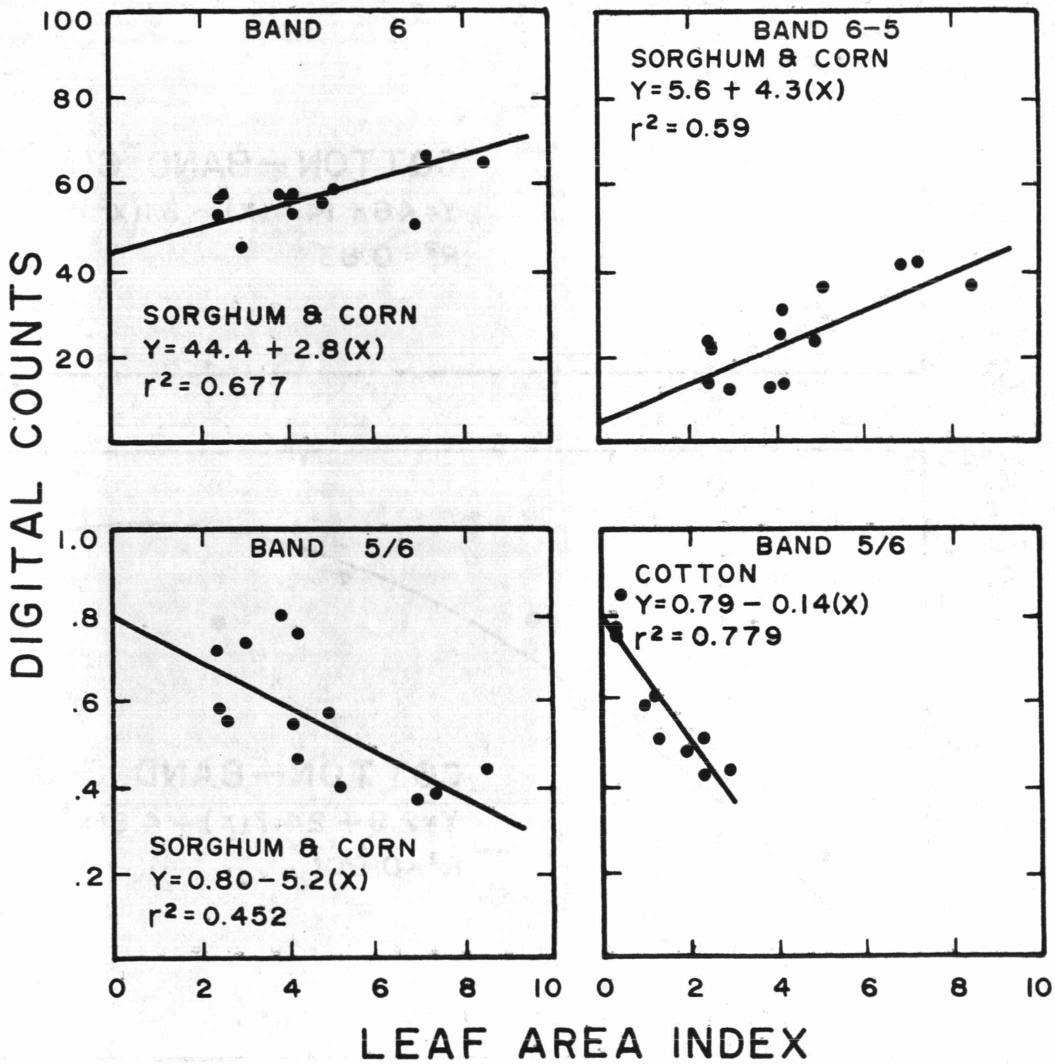

Fig. 3a. Combinations of CCT digital counts (band 6), digital count differences (band 6 minus band 5), and digital count ratios (band 5/band 6) for sorghum and corn combined into one crop type and for cotton versus LAI.

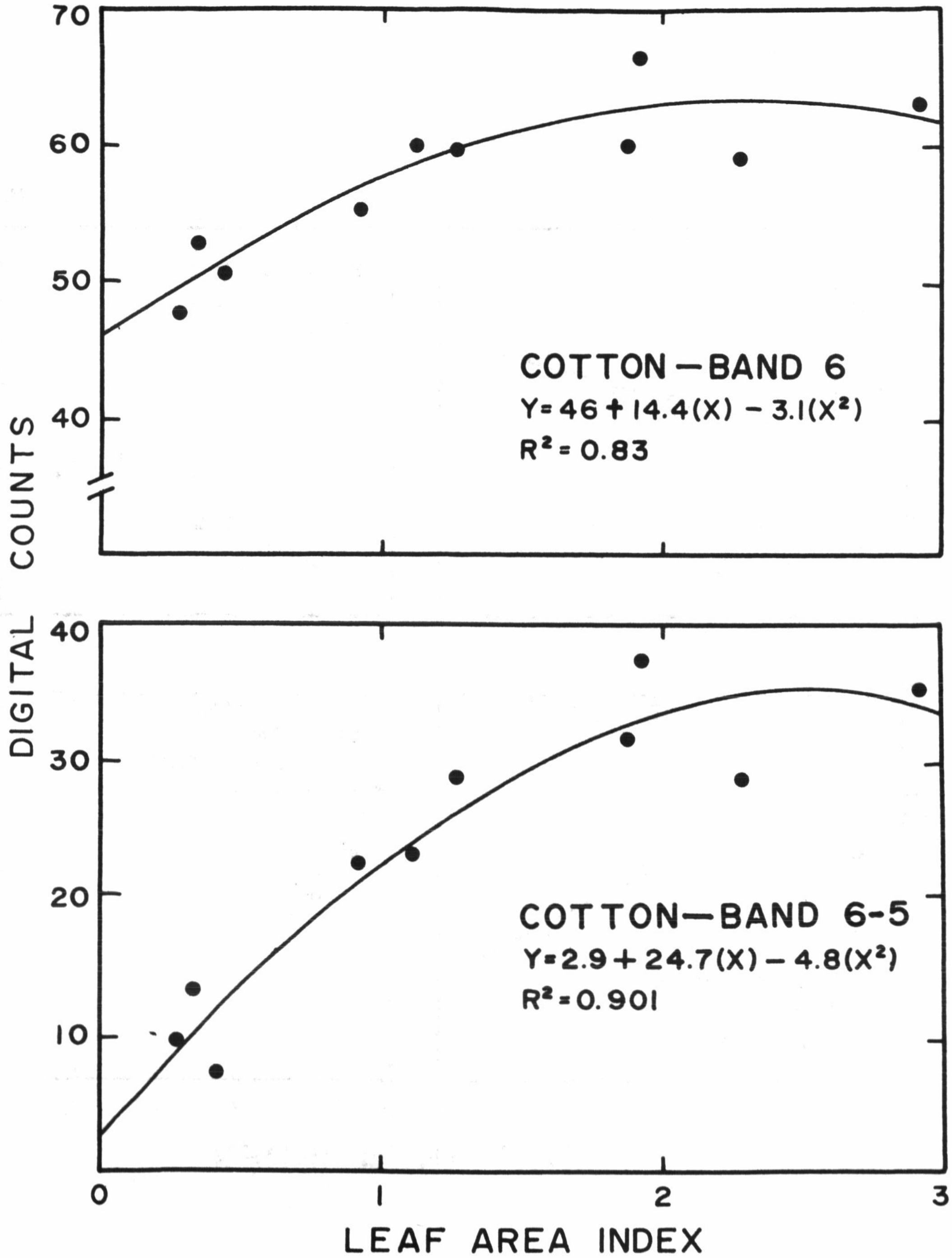

Fig. 3b. LAI of 10 cotton fields versus band 6 digital counts and band 6 minus band 5 count differences. In the regression equations Y symbolizes digital counts and X symbolizes LAI. R^2x100 is the percent of variation attributable to the relation between LAI and digital counts.